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RESEARCH AND DESIGN PROBLEMS INTRODUCED BY INCREASED POWER OUTPUT

By Oskar Kurtz

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RESEARCH AND DESIGN PROBLEMS INTRODUCED BY INCREASED POWER OUTPUT*

By Oskar Kurtz

There is a constantly increasing tendency toward the development of higher power units for the airplane. In this connection new research problems arise whose solution demands the investigation in particular of all the possibilities of further development of the Otto or spark-ignition engine. In what follows the question of the number and geometrical arrangement of the cylinders so important in the design of high performance power units will be considered from various points of view. A discussion will be given of the possibilities of the various working processes and an investigation will be made of possible means for improving the continuous operation and take-off performance, particularly the methods of supercharging, increasing the r.p.m., and employing the two-stroke-cycle engine. Finally, the question of lowered fuel consumption will be gone into briefly.

The subject will be treated under four headings:

I. Considerations on the engine lay-out.

II. Increase in output per given swept volume.

III. Improvement in the take-off performance.

IV. Lowering of the fuel consumption.

At the present time it cannot be predicted as to whether another type of airplane power unit with better performance will replace the spark-ignition and Diesel engines as an airplane drive. Even if there do exist at the present time some indications of the ultimate success, for example, of rocket type drive, steam drive, or internal combustion turbine, many years of investigation and development will still be required before the highly developed

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reciprocating engine will be replaced by something better.

Since the fact must be reckoned with that the Otto and Diesel engines will still dominate the airplane engine field for a long time to come, it is the urgent task of research, in addition to conducting investigations of other more promising methods, to investigate all the possibilities of further development of the reciprocating engine so that its fullest possibilities may be utilized.

Without going into the problem of very high-altitude flight which, as a special problem in itself, will not be given consideration in the present paper, the following questions are of fundamental importance for the further improvement of flight performance, namely, the form and layout of high-performance engines, raising of the engine power, improvement in the take-off performance, and lowering of the fuel consumption.

I. CONSIDERATIONS OF GEOMETRIC LAY-OUT OF HIGH-PERFORMANCE POWER UNITS

The tendency toward higher velocities of flight on the one hand and the requirement of high useful load on the other hand, bring with them the consequence that every country that has its own aircraft industry strives to develop the largest engine power possible consistent with low-performance weight. Although not all of the latest developments were exhibited at the most recent Paris exhibition, it was nevertheless noticeable that the number of airplane engines of high output was considerably increased. For these engines, not all of which were manufactured on a production basis, outputs of 1,000 to 1,400 horsepower were indicated as short-time full performance at sea level. Although, corresponding to the viewpoints and experience of each manufacturer, these designs showed differences as to structural form, number of cylinders, and cooling, there may, nevertheless, be observed a general tendency toward air cooling, particularly in the case of the large air-cooled, double-row radial engine with 14 or 18 cylinders. Of approximately ten types of engines of over 1,000 horsepower shown, seven - i.e., 70 percent - were air-cooled radial engines.

In view of this striving of engine manufacturers toward the development of engine types of increasingly higher output, it becomes necessary to give consideration to the question as to what structural types are to be given preference with respect to their power per unit weight, number of cylinders, and cylinder arrangement in order that some indication may be obtained as to the lines of development to be followed in the design of new types. The problem of cooling, with the losses associated therewith, will not be gone into here, since in what follows only constructional and thermodynamic features will be given attention. The question will be discussed from the point of view of total weight of engine, its mounting, and the effect on the aerodynamic efficiency of an airplane - whether in any particular case it is better to employ, instead of a single engine of high output, two smaller engines which may be mounted in the fuselage (Koolhoven type) or built into the wing as flat engines and connected by an intermediate shaft to the propeller. For a comparison of the drag relations for these various engine layouts and mountings, tunnel tests are still required. It is probable, however, that the future will see the justification of large as well as smaller power units corresponding to the purposes for which they were designed, since for high-altitude flight and steep climb the distribution of the power among smaller engines with several propellers appears to be advantageous, whereas for high-speed flight it appears to be more advantageous to employ a high power unit with a single propeller.

The important factors to be considered in the design of the engines, particularly the effect of the number of cylinders and cylinder size on the weight per horsepower, will be presented in a special report by Dipl.-Ing. Bensinger. The following discussion will be limited to a few of the questions concerning design features of high-output power units of 1,300 to 1,600 horsepower. It is here assumed that the manufacture of propellers to suit these outputs is possible.

In the past year a paper was presented by Wood (reference 1) on the raising of the output of an engine, and tables were set up giving design data, over-all dimensions, and displacement volumes for engines of 1,600 horsepower for various numbers of cylinders and lay-outs. According to this author the in-line engine of the future will be a machine with a six-throw crankshaft with several cylinders to each crank. He considers it difficult, however, using a solid crankshaft, to which he gives preference, to connect more than four connecting rods (with split big ends) to one crankpin. He accordingly envisages the development of the in-line engine in the form of an X engine with 24 cylinders. In the case of the radial engine, he believes that there will be an increase in the number of crankshaft throws, but a decrease in the number of pistons working on a single crankpin. There will be a corresponding decrease in the difference in the head resistance of the two-engine types.

In his lecture delivered at the beginning of this year, Fedden (reference 2) has considered these questions and discussed in particular the prospects of the air-cooled engine for the next five years. He is likewise of the opinion that there exists a demand for the development of engines up to 1,500-2,000 horsepower. In view of the weight per horsepower and the manufacturing costs, however, he leans away from too great an increase in the number of cylinders and sees the future development of the air-cooled engine tending toward single-row and double-row radial engines and multi-row engines. The installation of the horizontally opposed engine completely within the wing, he also considers as giving promise.

Figure 1 gives a comparison between the present engine characteristics and the values which will be approached in the near future with increased piston speeds and booster pressures. The values assumed by Wood, which are based on a piston speed of c_m = 15.3 m/s (about 3,000 ft./min.), and a mean effective pressure, p_e = 12 kg/cm^2 (about 168 lb./sq.in.), are likewise shown. According to the figure, for an engine of 2-liter capacity, speeds of about 3,300 r.p.m. with displacement performances of 45 horsepower per liter (0.74 hp./cu.in.), will be attained. Whether such high piston speeds could be attained with the usual poppet-type valve gear, cannot be predicted in view of the absence of data in Germany. For short-time operation, speeds of 16 m/s (3,150 ft./min.) are indicated for the Bristol Pegasus engine. It may be assumed, however, that with the further development of the sleeve-type valve gear, there are well-grounded reasons for believing that the present difficulties will be overcome and these values of piston speed realized.

Table I and figure 2 summarize the cylinder dimensions for various geometrical cylinder lay-outs, the required frontal areas, speeds and weights, and will serve for a comparison of the merits of the different cylinder arrangements. An engine output of 1,000 horsepower, attainable at present, is assumed - this will correspond in a few years to about 1,300-1,600 horsepower - and numbers of cylinders from 9 to 32 are considered. According to the studies carried out by the Institute for Engine Design on the number of cylinders and cylinder size, the weights and dimensions may to a certain approximation be predicted from certain assumptions with regard to the stroke-bore and connecting-rod ratios. In the table the weight required for cooling is included in the case of the radial engine but not in the case of the liquid-cooled in-line engines, all of which have equal radiators. It is found that in certain types of design the weight and frontal areas come out to such values as to make them practically inapplicable. The 16-cylinder V and horizontally opposed engine, the 32-cylinder X and H, as well as the 18-cylinder radial engine are favorable while the 12-cylinder V, the 24-cylinder H and X, and the 14-cylinder radial engine are somewhat less advantageous. All other lay-outs are inapplicable for the power under consideration. The 32-cylinder engines in the X and H arrangements are, to be sure, quite small in cross section, but in spite of their favorable weight/power ratio it is doubtful whether such a large number of cylinders, on account of the associated high manufacturing cost and the many structural parts required will find actual application. The 16-cylinder V engine and the 24-cylinder H and X engines with 60° angle, on the other hand, offer quite practical solutions for the power here assumed. The 16-cylinder H or X engines show up unfavorably, however, and give little promise of development. Even the 24-cylinder X engine with 90° angle receives a somewhat large cross section, although this arrangement will probably find justification for particular purposes. The question whether in the case of the 24-cylinder engine, the H arrangement with two crankshafts or the X arrangement with a single crankshaft, has the advantage, cannot as yet be answered definitely. According to our investigations no essential difference in weight will result. In the case of larger airplanes with thick wings, the horizontally opposed engine installed within the wing at right angles to the direction of flight, with remote propeller drive, will practically not increase the head resistance. In any case, this arrangement requires a special wing construction. This opposed-engine type of arrangement has already been the subject of many investigations and has been practically applied, for example, to the 12-cylinder Potez engine. On account of the compromises made necessary in the airplane structure, however, this arrangement will always be limited in application. In recent literature the advantages of the horizontally opposed arrangement have often been emphasized. A further study, however, from the point of view of the airplane structure is necessary before any definite conclusions as to its advantages may be reached.

The foregoing considerations on the various possibilities of lay-out of high-performance engines cannot, naturally, include all possible points of view which in any particular case determine the design. The ease and cost of production will have to be taken into account as well. In particular, the above-indicated relations will vary if, for some particular reason - in the case of a Diesel engine, for example, in view of the high compression ratios - higher bore-stroke ratios will have to be chosen. The conclusion reached by Fedden, namely, that too small cylinders should not be chosen has, as will later be shown, a certain justification.

A question that has not yet been solved experimentally and which cannot be discussed in this connection, is the behavior of air cooling at the higher altitudes. To throw light on this problem, investigations on the heat transfer at high-altitude conditions and single-cylinder investigations at the high-altitude climatic conditions are necessary, after which the advantages of the two types of cooling will be better understood.

In the choice of the number of cylinders and the swept volumes when new designs are contemplated, the required high-altitude performance must be given consideration since the supercharger output must still be supplied by the engine and the highest attainable pressure ratio is limited by the engine. Furthermore, the admissible supercharge pressure must take into consideration the start of engine knocking, which is essentially determined by the supercharge temperature. Considerations on the high-altitude performance and the thermodynamics of the engine with exhaust turbine supercharging, will not be gone into here, since they will be the subjects of separate reports. Even if it does become possible within a short time to develop spark-ignition engines with exhaust-turbine superchargers, the gear-driven supercharger will nevertheless continue to be used also in the future for certain purposes with further improvement in output and efficiency.

As a complement to the foregoing remarks, it is worth while to investigate the relations between the piston diameter and the number of cylinders for high-altitude engines with mechanical superchargers. As an example, let two engines be chosen which at 8 kilometers (about 26,000 feet) altitude deliver 1,200 and 750 horsepower, respectively, and are provided with single or two-stage superchargers for this altitude. The adiabatic supercharger efficiencies are assumed to be 65 and 76 percent, respectively. Although these values are as yet not attainable, they will be approached in the near future since there are well founded reasons for believing so. Figure 3 shows the computed relation between the number of cylinders and the cylinder bore where for the mean piston velocity the common present-day value of 13 m/s (2,600 ft./min.) has been assumed and a compression ratio of 6.5. The practical range for the piston diameters is limited between 120 and 160 mm (4.76 and 6.35 in.). The numbers of cylinders given in the figure are the structurally feasible ones mentioned above. In both cases the admissible supercharge temperature was taken to be 350° K. where for $\eta_{ad} = 0.65$, the supercharge pressure is 0.9 atmosphere, and for $\eta_{ad} = 0.76$, it is 1.1 atmospheres. In the region of small numbers of cylinders the curves run very steep and flatten out as the number of cylinders increases; that is, with too strong a decrease in the cylinder bore the number of cylinders rapidly increases. It therefore follows that within this region the advantages which are obtainable by a decreased cylinder bore will hardly make up for the rapidly increasing disadvantages of a high number of cylinders. It is further seen from the figure that, for example, for a bore of 158 mm in the case of a 1,200 horsepower engine and a supercharger efficiency of $\eta_{ad} = 0.65$, 18 cylinders will be required, whereas for $\eta_{ad} = 0.75$, the corresponding number will be only 16. If cylinders of 120 mm were used it would lead to a structurally expensive 32-cylinder engine, whereas with a 136 mm bore it will still be possible to use a 24-cylinder engine. For $\eta_{ad} = 0.76$, the 24-cylinder arrangement could be used with 116 mm bore. Too great a reduction in the cylinder dimensions would thus lead to a structurally disadvantageous number of cylinders as pointed out by Fedden. Even with the fuels at present available for continuous operation the supercharge temperature of 77° should set an upper limit. The reduction of the total swept volume below a certain value, however, would make supercharge cooling necessary with all the associated structural disadvantages since it will be necessary to apply higher supercharge pressures.

The figure further shows that the improvement in the supercharger efficiency is also of great significance for the structural lay-out of high performance units. These considerations bear particularly on the continuous operation at the working altitude assumed. It will later be pointed out that for take-off and climb smaller cylinders, which permit higher supercharge pressures, are more advantageous.

II. THE INCREASE IN THE OUTPUT PER UNIT DISPLACEMENT VOLUME

Prospects of Various Working Processes

In order to attain the above-mentioned values (p_e = 12 kg/cm²*, c_m = 15 m/s (3,000 ft./min.)) with the high-performance power units, much research is still required. Before taking up the various methods of attacking the problem a brief discussion will be given of what prospects are offered by the several known working processes, particularly for the airplane engine. Figure 4 shows the results of an investigation by the Institute for Thermodynamics and Working Processes on the various attainable performances for three different processes, namely, the injection Otto engine, the four-stroke-cycle and the two-stroke-cycle Diesel engines with supercharger driven by the engine and by exhaust turbine. The values are for a forward velocity of 400 km/h (about 250 mi./hr.) at sea level and were computed on the basis of the polar of an airplane such as is used today. The air-excess ratios shown in the figure have already been partially attained or will certainly be attained shortly. For each altitude the required supercharger output is shown. Assumptions must further be made as to the efficiencies and sizes of radiators, concerning which there are as yet no experimental data available. The curves are therefore useful in indicating the order of magnitudes involved and may change as further data are obtained on new supercharger processes. The absolute altitude performances are not comparable since the outputs per displaced volume are different for the power units investigated. In the case of the two-stroke-cycle engine, the well-known highly developed and advantageous scavenging process of Junkers, whose efficiency should hardly be exceeded by any different type of structure, has been assumed. High-altitude engines with other scavenging processes used

*(168 lb./sq.in.)

at present would in all cases show up to disadvantage. Two-stroke-cycle Otto airplane engines have not yet been built, therefore no information on them is as yet available. More will be said later about the possibilities of development of this type of design. The essential result of these considerations is that at higher altitudes the propulsive outputs referred to the sea-level output (not the absolute outputs, which in the case of the Otto engine is in all cases greater due to the higher output per liter) do not differ much from each other. In particular, it is to be noted that also the four-stroke-cycle Diesel process shows promise. The fact that the curve here lies higher is the result of the small expenditure required for the exhaust cooling. The questions of the fuel consumption and range still require special investigation. Similarly, the question of weight/power ratios, which in the case of the Diesel engines with their larger dimensions should be somewhat higher, will not be gone into here.

Increase in Performance through Supercharging

In the case of the 4-stroke-cycle Otto engine, considerable increase in output has, in recent years, been made possible by the development of new fuels denoted as "100 octane." These fuels permit higher compression ratios and supercharge pressures and therefore may also affect the engine size for a given output. The effect of the 100-octane fuels on the dimensions and power/weight ratios will not be considered here since test data are still unavailable. Fedden has already discussed the possibilities of such fuels and has divided the future power units into 87-octane and 100-octane engines. For supercharge operation still further studies are to be made on the scavenging possibilities and the admissible supercharge pressures for continuous operation. The latter factor, as has already been mentioned, is of prime importance with respect to the magnitude of the displaced volume and the fuel consumption. The question of the lowering of the waste heat on the application of higher supercharge pressures to obtain higher short-time performance at take-off will be considered later.

Figure 5 shows the attainable mean effective pressures obtained from single-cylinder tests at various supercharge pressures and with different valve timing, and also shows the fuel and air consumption. With the proper choice of valve timing and lower supercharge temperatures, considerable increases may be obtained in the mean effective pressures without any appreciable increase in the specific fuel consumption. This increase in output is also accomplished by the scavenging of the combustion space, such scavenging being successfully applied, as is known, to Diesel engines and leading to a lowered temperature at the end of the compression stroke and a better volumetric efficiency. Investigations already started on this subject are to be complemented by further studies, extending the investigations to higher rotational speeds. The question as to whether it is worth-while changing the valve timing during operation, as has at various times been proposed, needs further explanation. Several investigators - for example, Ricardo (reference 4) - have recommended "stratified" supercharging as a means for increasing the performance and lowering the fuel consumption. In practice, it will not be simple to obtain such stratification, particularly at the higher rotational speeds. It is nevertheless desirable to ascertain whether such stratification is possible, whether it is likely to be successful, and whether the additional structural weight made necessary, is justified.

Caroselli, in an investigation on engines with mechanically driven superchargers for a nominal altitude of 6 km (20,000 ft.), has considered the question of the most favorable supercharge pressures to apply and came to the conclusion that, for example, an engine with a degree of supercharge of 1.3 and with a supercharge stage that can be disconnected or with a controllable supercharge drive offers the advantages of small frontal area and high take-off performance but in other respects - for example, that of fuel consumption - is inferior to the low supercharge engine and so is inapplicable for large ranges.

Another constructional and theoretical investigation has further confirmed the result previously obtained in the considerations on cylinder size, that very small cylinder dimensions such as are common in racing automobiles using high supercharge and high piston speeds have no advantages for large airplane engines since the saving in weight which results from the smaller displacement volume, is offset by the increased size of the supercharger. With high supercharge for full-load performance at 6 km, for example, a supercharger for 8 to 9 km would be necessary and hence, also, supercharger cooling would be required. The possibility of further development of such an engine is therefore very limited so that this line of investigation offers no promise. It would, moreover, be necessary to apply multistage supercharge in order to obtain adequate take-off performance.

In this connection it may be worth-while to investigate what these relations would be on the introduction of a stageless regulation of the supercharger without any losses, the significance of which was pointed out by Nutt in his lecture last year before the Lilienthal Society. The example previously chosen of an engine of 8 km working altitude will again be used. On this engine investigation was made to determine what performances in climb were attainable under the assumption that normal 87-octane fuel was employed and that a highest admissible supercharge temperature of 350° K, corresponding to 77° C. was not exceeded.

Figure 6 shows the computed outputs for various supercharger pressures in percent of the engine output at 8 km flying altitude. No cooling of the supercharge air between the supercharger and the engine is provided. The continuous line represents the upper limit of output obtainable at a supercharge temperature of 77° C. The dotted lines give the outputs at various supercharge pressures between the limits of 1.16 and 1.5 atmospheres. In climbing flight the supercharge pressure must be held constant up to the point of intersection with the boundary line by means of a regulator, while from there on after reaching the highest permissible temperature the supercharge pressure must be lowered. Although it is again seen from these considerations that engines with small pistons - for which, on account of the smaller waste heat, higher supercharge pressures are permissible - have the advantage over large piston engines in climb, it is nevertheless clear that too high a supercharge - for example, above 1.5 atmospheres - gives no further appreciable advantages and the time during which these supercharge pressures may be applied becomes shorter if no special means are taken for lowering the waste heat.

Summarizing, the following may be definitely stated with regard to the questions of cylinder size and supercharge. Structural advantages with regard to weight/power ratio and frontal areas are to be expected from the application of small cylinders. On account of the displacement volume required of high-altitude engines when the dimensions are reduced below certain values, however, a large number of cylinders, with the associated structural disadvantages, becomes necessary. Small pistons are favorable for climb but the high supercharge leads to increased structural weight on the part of the supercharger. The decision as to the one or the other tendency must be made in accordance with the object that it is desired to attain.

Increasing the Speed of Rotation

The tendency toward increased piston speeds up to 15 or 16 m/s has already been referred to. It is a question whether this method, if no other difficulties arise at the piston, gives any further advantages when used with the poppet-valve gear. Caroselli had previously established the fact that in the case of airplane-engine cylinders a mean velocity at the valve inlet sections of 60 m/s (12,000 ft./min.) gives the best volumetric efficiency and the maximum mean effective pressure, and that a velocity of 90 m/s (18,000 ft./min.) should not be exceeded. Although these velocities are still considerably above those which Ricardo had determined as most favorable for automobile engines, it is a fact known to every engine builder that in certain types of cylinder-head designs it is difficult to employ large port areas and that the acceleration forces set a limit to the increase in the valve lift. An improvement of the inlet port areas is expected from the use of the sleeve-valve gear which so far has been applied only by Bristol. Theoretical investigations have shown that with suitable sleeve-valve designs more favorable time areas may be obtained than with the usual valve gear. Naturally, this is not the only point of view from which the sleeve-valve gear is to be judged. Other advantages which have often been brought out in the literature on the subject and are therefore assumed to be well known, similarly speak in favor of the sleeve-valve gear, so it is desirable that research and development work be continued along this line.

Figure 7 shows a comparison of the mean effective pressure as a function of the speed for a very good poppet-valve engine with the values to be expected from a sleeve-valve engine. The poppet-valve engine which was run with a supercharge pressure of 1.3 atmospheres, had the most favorable port areas obtainable. Although for a speed of 2,300 r.p.m., the mean velocity of the gas at the inlet is v_g = 50 m/s (10,000 ft./min.), the mean effective pressure drops after this speed. In the investigations on the sleeve-valve gear, however, the pressure increased almost linearly up to about v_g = 100 m/s (20,000 ft./min.). Whether this is due to a better discharge coefficient or to less heating of the charge in flowing in, has not yet been determined. Further investigations along this line are necessary to throw light on these processes. It is safe to assume, however, that with the sleeve-type of valve gear considerable further improvement in the performance of the Otto engine may be expected.

The Two-Stroke-Cycle Process in the

Otto (or Spark-Ignition) Engine

In the discussions on the improvement in performance of the Otto engine, the question always arises as to whether a further decrease in the weight/power ratio cannot be attained with the two-stroke-cycle process. In this connection it is often wrongly assumed that the two-stroke-cycle practically doubles the output per unit of swept volume. Unfortunately, however, on account of the higher heat loading of the piston and the reduction in the effective stroke by the scavenging ports, only a portion of the expected increased output as compared with the 4-stroke-cycle for equal piston velocity is obtainable, in view of which the lack of data available cannot be definitely specified. Unquestionably, a two-stroke-cycle engine, provided it may be run with a reasonable expenditure in scavenging air, has the advantage of a uniform turning moment and smaller inertia forces, and hence lower structural loads, so that some economy may be expected in structural weight.

At the author's initiative and following some suggestions by Lutz, some preliminary investigations have been conducted on the possibilities of several types of familiar valve gears and a brief discussion of them will be given here.

In laying out a design for a two-stroke-cycle engine, it is first of all necessary to see that the valve gear provided gives the required areas for allowing the expansion of the gases and for scavenging. Under the assumption of equal piston speeds, several arrangements may be compared, referring the port areas to the piston area. Figure 8 shows a comparison of four different two-stroke-cycle cylinders with familiar types of valve gear, namely, an opposed-piston engine, a four-valve, two-stroke-cycle engine with scavenging from below by piston-controlled slots, a rotating sleeve-valve engine, and a roller sleeve-valve engine with similar scavenging. In the case of all four cylinders the same crank angle is assumed for the total exhaust time. It is further assumed that the outputs are the same for all the cylinders. The diagrams show the variation of the opening of the outlet areas as well as the magnitude of the mean outlet area referred to the working piston area. For all cylinders equal scavenging time areas per cm^2 of piston area are provided for which the inlet times are given in the figure. The mean areas from the beginning of exhaust up to the opening of the scavenging ports are also shown. These cross-sectional areas are of prime importance for the expansion process of the exhaust gases. The advantage of the opposed-piston engine is clearly brought out. The same port areas may probably be attained with the U-cylinders, for which similar relations apply. From the comparison between the uniform motion of the sleeve-valve gears with the nonuniform opening of the poppet-valve and opposed-piston engine, it is seen that for equal maximum openings the two last-mentioned types of valve gears have a clear advantage from the point of view of the control of the scavenging and exhaust processes. It is to be observed, however, that the design of a separately driven, nonuniformly moving valve gear member is kinematically and dynamically not simple to carry out with high-speed engines without encountering difficulties. Thus, for example, with the four-valve cylinder shown, the accelerations set up already lie close to the present-day limits. With nonuniformly moving sleeve-valve gear, similar difficulties will naturally be met with. The comparison of the different arrangements brings out, however, also the following. With the opposed-piston engine the inlet and outlet close simultaneously whereas with the other designs the application of equal specific inlet and outlet time-areas leads to earlier closing of the inlet. For high altitude engines such an arrangement is not feasible on account of the scavenging-air loss so that for these systems it is practically required that the outlet angle be chosen smaller than is here assumed for comparison. Taking account of the possibility of after-charging in order to utilize fully the required scavenging pressure it may even be found desirable to close the inlet after the outlet. Figure 9 shows that these requirements lead to the result that an engine like the two-stroke-cycle rotary sleeve-valve engine here presented shows no promise of success. The figure shows the expansion of the exhaust gases against the piston displacement as determined by computation. The expansion to the scavenging air pressure is first completed near the lower dead center so that practically no time is available for scavenging whereas the minimum scavenging angles required amount to about 80 crank-angle degrees and the inlet must open 40° before the lower dead center.

The above simple types of design with the impaired scavenging conditions thus offer no promise for high-output power units unless new methods showing fundamental improvements are found. In the case of the favorable double-piston engine or the engine with U-cylinders increased structural weight is required. Information concerning the heat loading of the piston and the scavenging efficiency can only be provided by tests. On the application of greater piston areas it will probably be difficult to take care of the heat loading of the Otto two-stroke-cycle engine. On the other hand it appears possible, in the case of small sporting and training airplane engines for which also no high charging is necessary, to apply the two-stroke-cycle process. Investigation on this point would be desirable.

III. IMPROVING THE TAKE-OFF PERFORMANCE

The foregoing considerations on the improvement in performance by supercharging assume the application of normal fuels of 87 octane number and the maintenance of an admissible temperature of the charge permitting no knock operation (about 77° C.). In take-off, however, under certain conditions, such as for example, in the case of airplanes with very high wing loading or where small flying fields are used high short-time loads cannot be avoided. The required increase in the charge pressure leads, however, to higher charge temperatures than were indicated above and therefore to knocking and to such high cylinder and piston temperatures that piston seizing and overheating may result. Ways will therefore be sought to reduce this great loading. The following possibilities show promise for attaining this object. These are well known but must still be compared as regards practical application.

a) Application for take-off of a special fuel that permits high charge pressures and temperatures without the danger of knocking.

b) Injection into the combustion space of water, the evaporation of which lowers the compression and combustion temperatures.

With regard to the above possibilities several investigations have been conducted which, although not giving a complete answer to the question, do provide data that indicate the lines of further study to be followed. Figure 10 shows the behavior of several important fuels used with supercharged engines and brings out the fact, already familiar to some extent, that the octane number offers no scale of comparison for the knocking behavior in the case of supercharger operation and that under these operating conditions another series of fuels different from those used with the C.F.R. engine tests must be applied. Of particular advantage is the three component mixture consisting of 30 Bi, 40 Bo, and 30 alcohol, and giving an octane number of 90. This mixture was applied in comparison tests on a BMW VI single-cylinder engine (compression ratio 7.3) with normal aviation gasoline of 87 octane and water injection and the results are shown in figure 11. With the aviation gasoline two series of tests at fuel temperatures of 55° and 100° C. were carried out and with the mixture only one test at 100° C. The quantities of water required for no-knock operation are also indicated on the figure. With the aviation gasoline of 87 octane and at a temperature of the charge of 55° C. knocking sets in at 1.1 atmospheres supercharge and at 100° C. temperature knocking is set up below supercharge whereas the mixture without the addition of water admits of a pressure of 1.36 atmospheres without knocking. No-knock operation is thus still possible for the mixture with slight water expenditure. In the case of the gasoline with water injection there will be no knocking up to a pressure of 1.6 atmospheres. The increase in the pressure of the charge corresponds to an increase in the mean effective pressure. The quantity of water that must be injected with the 87 octane aviation gasoline before the knocking of the mixture sets in is considerable and at 100° C. is about double the amount at 55° C. The cooling effect shows up in the lowering of the exhaust temperature. If these two results are compared it will be seen that at a temperature of the charge of 100° C. and with respect to normal start of knocking at a pressure of 1.35 atmospheres 35 percent more output can be obtained with the mixture, while with "stanavo" about 30 percent more, and with a water consumption of 70 percent of the fuel consumption, in both cases with no-knock operation.

Naturally, no final conclusion can be drawn on the basis of these test results obtained on a somewhat old type of cylinder and at low piston speed. Further investigation under conditions of water cooling, air cooling, and greater speeds is required. It is to be expected, however, that the advantage of the mixture fuel will remain also at higher heat loading, that water injection, which carries with it certain disadvantages will not be required, and that a special fuel for take-off, as has already partially been applied, will enable knock-free operation also at high supercharge pressures.

IV. LOWERING OF THE FUEL CONSUMPTION

Finally, the reduction of the fuel consumption is an important factor in the further development of the Otto engine, particularly for the long-range engine. In the foreign literature there have in recent times appeared reports purporting to have succeeded in attaining extremely low specific fuel consumptions even bettering those of Diesel engines. Figures of 150 g/hp.hr. (0.33 lb./hp.hr.) are cited without any indication being given, however, for what output these values were attained and whether they referred to engines on the ground with low-loading or high-altitude engines. Investigations of this kind have for some time been conducted under the supervision of the DVL that rely mainly on previous investigations of Löhner on operation with excess air.

Figure 12 shows the result of a laboratory single-cylinder test carried out on a modern test cylinder at n = 2600 r.p.m., a compression ratio of 7.7 and using an aviation gasoline with an increased lead content (octane number about 90) and without supercharge. It may be seen that the minimum value of the consumption lies within a region of excess air ratios of 1.1 to 1.2 agreeing well with the previous tests of Löhner. On the single cylinder, which has a relatively bad mechanical efficiency, a full consumption of about 182 g/hp.hr. (0.4 lb./hp.hr.) was measured. The region within which this minimum value applies is very limited. In any practical case it will be difficult to keep within this range due to difficulties in mixture distribution and somewhat higher values will be met with which in this case of multicylinder engines should be of the order of 170 to 180 g/hp.hr. Fedden reports a fuel consumption of 176 g/hp.hr. in cruising flight at 60 percent of full load. The results of the DVL give quite good agreement for practical conditions, with those of Fedden. With supercharger operation the diagram changes insofar as the fuel consumption becomes naturally somewhat higher but the region of minimum values becomes somewhat flatter. Conclusive data are as yet not available. The discussion here given is meant to serve only as a contribution to this problem and is intended to lead to further studies.

In the foregoing discussion only a small portion of the field of investigation has been considered, which is of importance for the further development of power units in the near future. In the highly developed state to which engine design has already attained further progress will no longer be by sudden jumps and the problems for investigation and development will become more and more difficult as greater refinements and improvements in the working processes are achieved. It is to be expected that still greater power units will be built and that the weight/power ratio will further be reduced. Some of the ways indicated in this report for raising the mean effective pressure and the piston velocity, in connection with which in particular the sleeve-valve type of gear offers new possibilities, appear to be suitable as means of approaching this subject.

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3. Nutt, Arthur: Aircraft Engines and Their Operational Problems. Paper read before the Lilienthal Society, Oct. 12-14, 1936. Luftwissen, vol. 3, no. 10, 1936, pp. 287-298.

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TABLE I

Characteristics of 1,000-Horsepower Airplane Engine at

V_k = 13 m/s (about 2,500 ft./min.) (s/d = 1.0) and

1.2-atmosphere supercharge at 4 kilometers altitude

Number of cylinder	9	12	14	16	18	24	32
Horsepower/cylinder	111	83.3	71.5	62.5	55.5	41.7	31.3
Cylinder capacity, liters	4.9	3.12	2.48	2.03	1.7	1.12	0.74
Stroke and bore	184	158	147	137	129	113	98
r.p.m.	2120	2470	2660	2840	3020	3450	3980
Section of engine nacelle through front cylinder							
V engine	-	0.53	-	0.43	-	-	-
X engine	-	-	-	0.86	-	90°:0.6 60°:0.54	0.43
H engine	-	-	-	0.73	-	0.51	0.38
Flat engine	-	-	-	0.38	-	-	-
Radial engine, diameter (m)	1610	-	1190	-	1130	-	-
Weight							
V engine (kg)	-	660	-	620	-	-	-
X engine (kg)	-	-	-	710	-	640	605
H engine (kg)	-	-	-	620	-	640	605
Flat engine (kg)	-	-	-	-	-	-	-
Radial engine (kg)	710	-	640	-	615	-	-

Translation by S. Reiss,
National Advisory Committee
for Aeronautics.

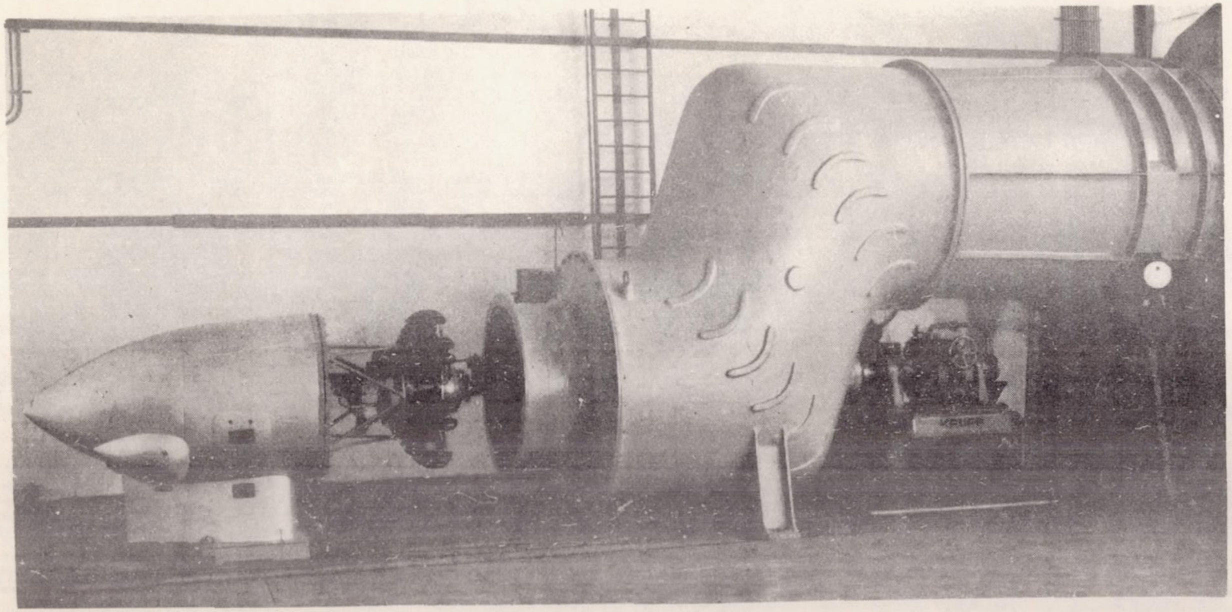


Figure a.- Test set up for air-cooled airplane engines in the Institute for Power Plant testing of the DVL.

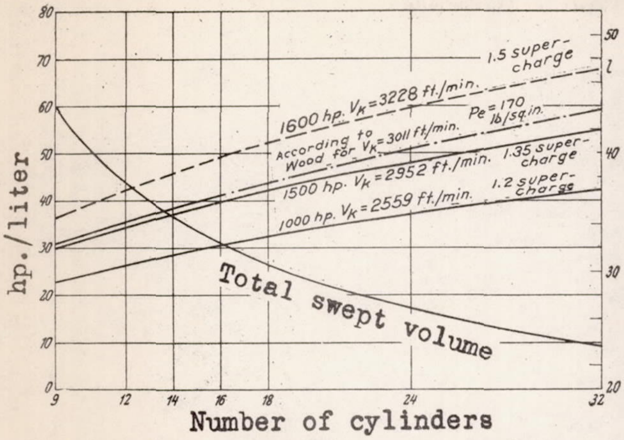


Fig.1.- Output per liter as a function of the number of cylinders.

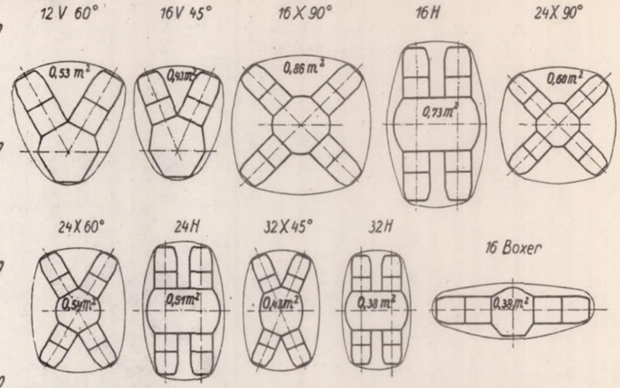


Fig.2.- Frontal areas for liquid-cooled engines of 1000 hp. (V=2600 ft./min.; stroke/bore=1.0, supercharge pressure = 1.2 at. at 13000 ft. altitude).

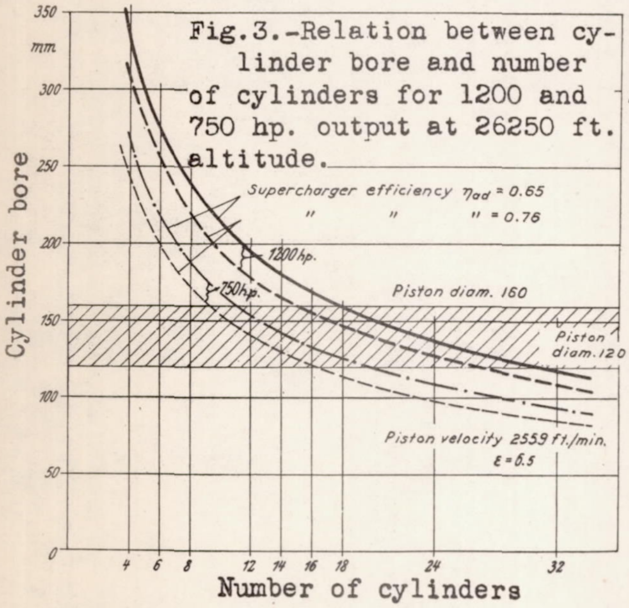


Fig.3.-Relation between cylinder bore and number of cylinders for 1200 and 750 hp. output at 26250 ft. altitude.

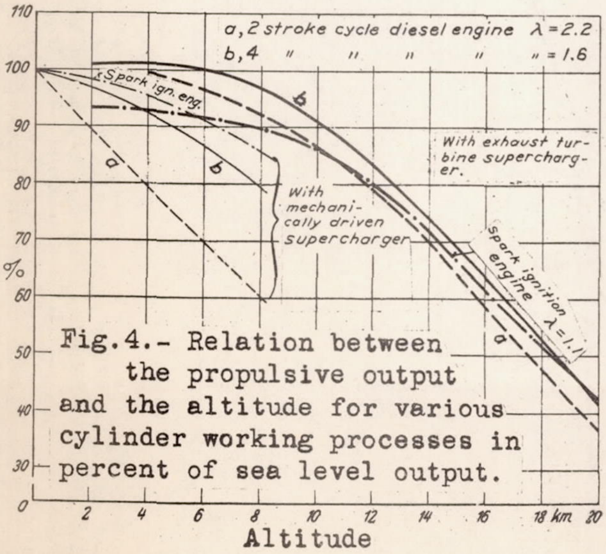


Fig.4.- Relation between the propulsive output and the altitude for various cylinder working processes in percent of sea level output.

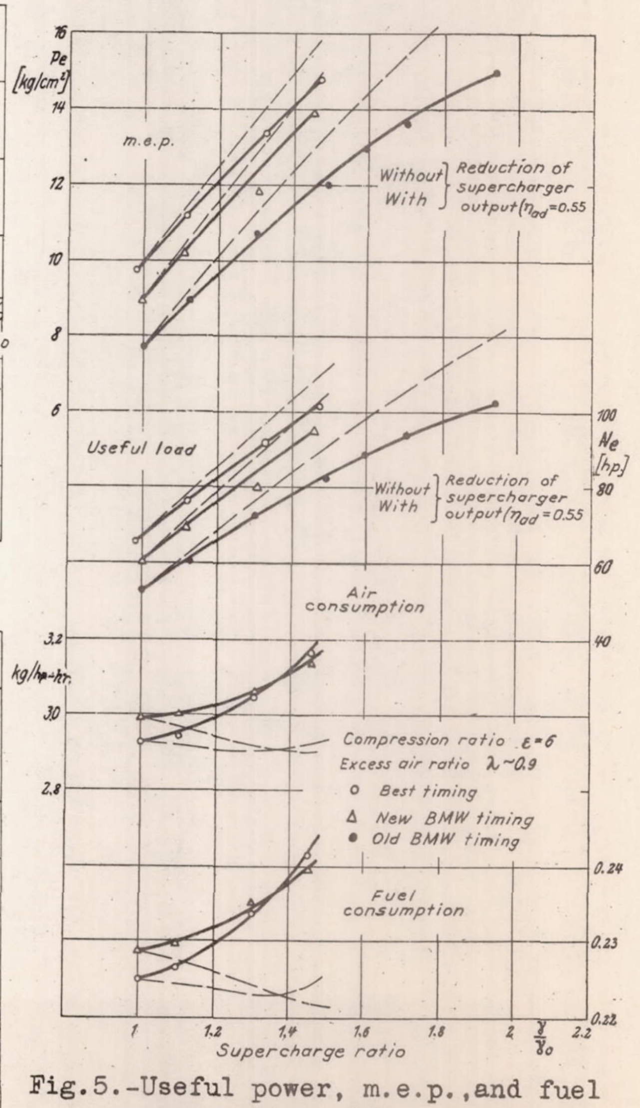


Fig.5.-Useful power, m.e.p., and fuel consumption with supercharger operation.

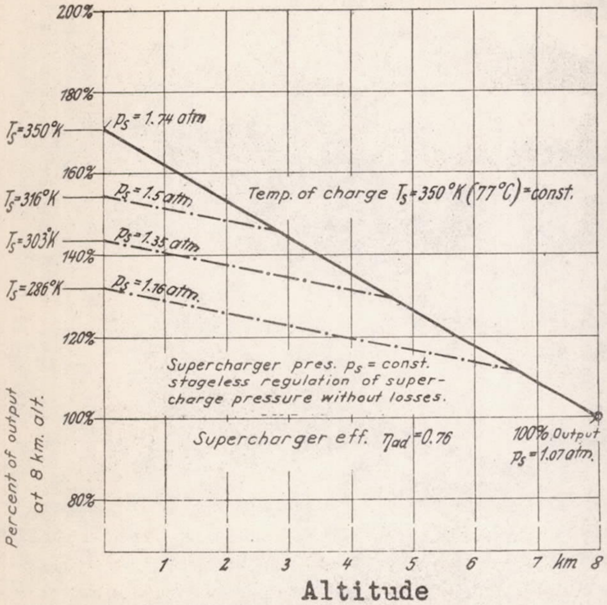


Figure 6.- High altitude performance for stageless regulation to constant supercharge pressure and supercharge temperature.

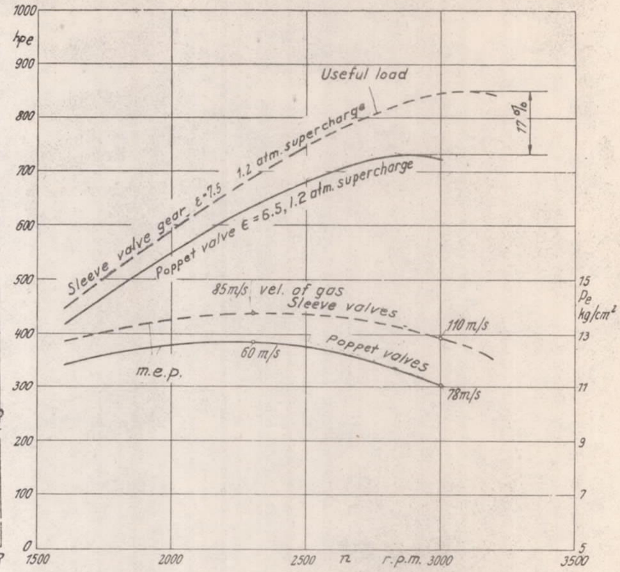


Figure 7.- Useful power and mean effective pressure for an engine with poppet and sleeve valve gear.

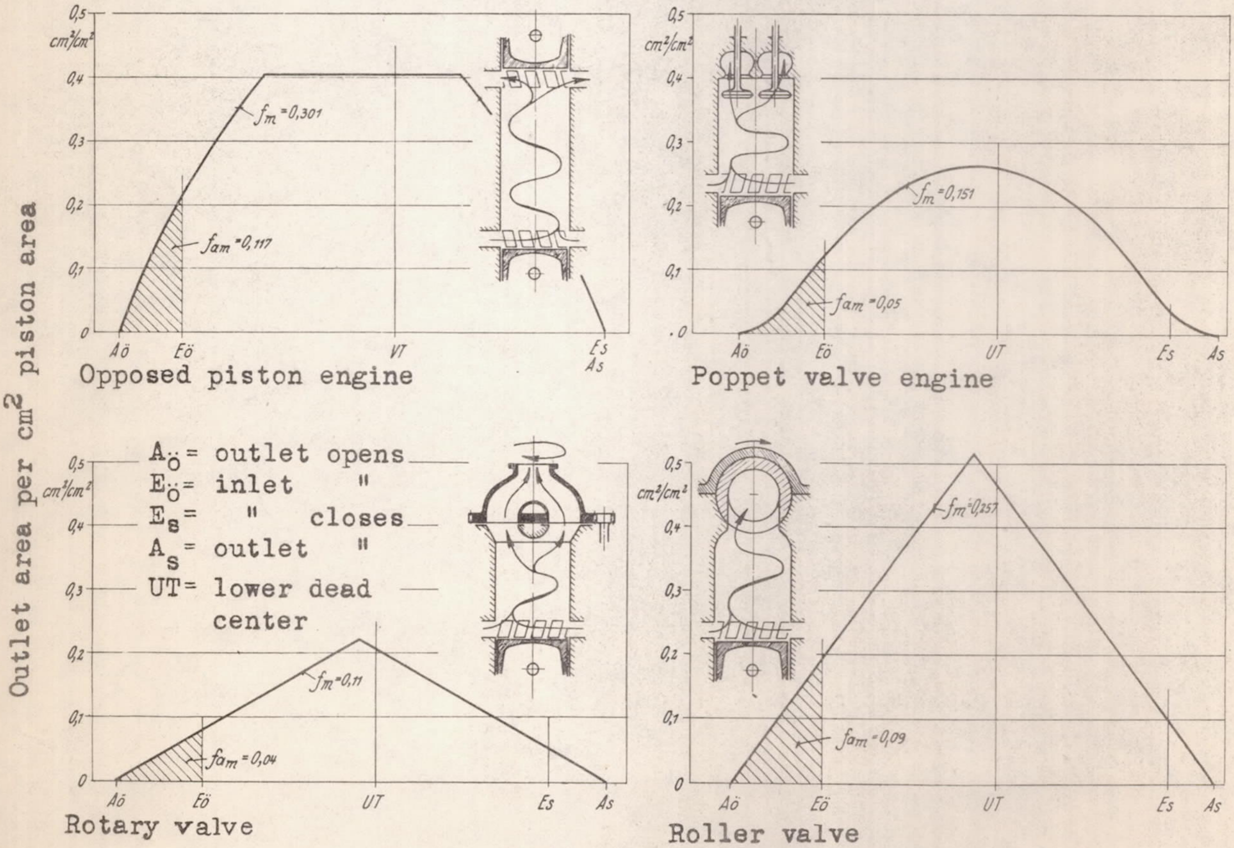


Figure 8.- Valve gear sections for two-stroke cycle cylinders with various outlet valves.

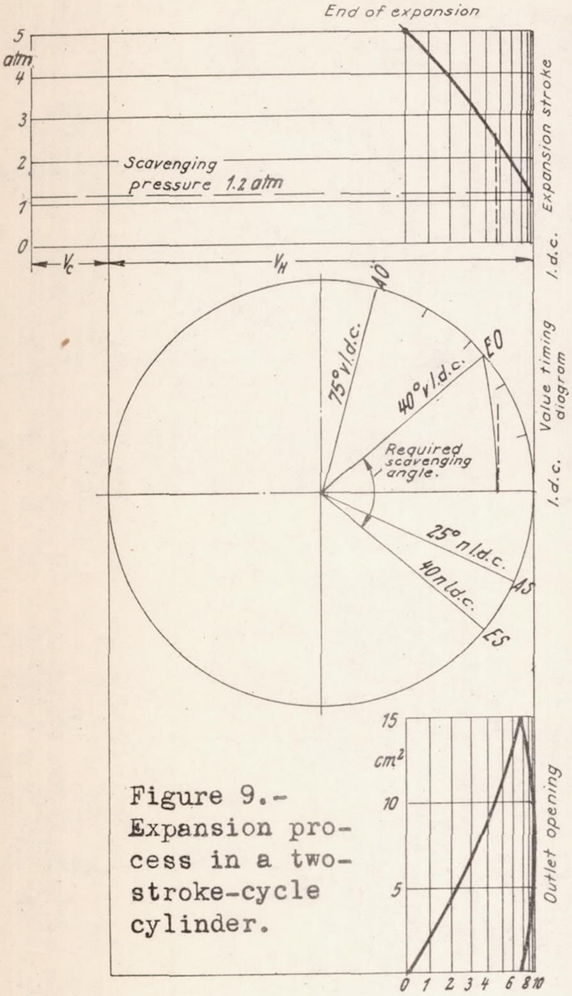


Figure 9.- Expansion process in a two-stroke-cycle cylinder.

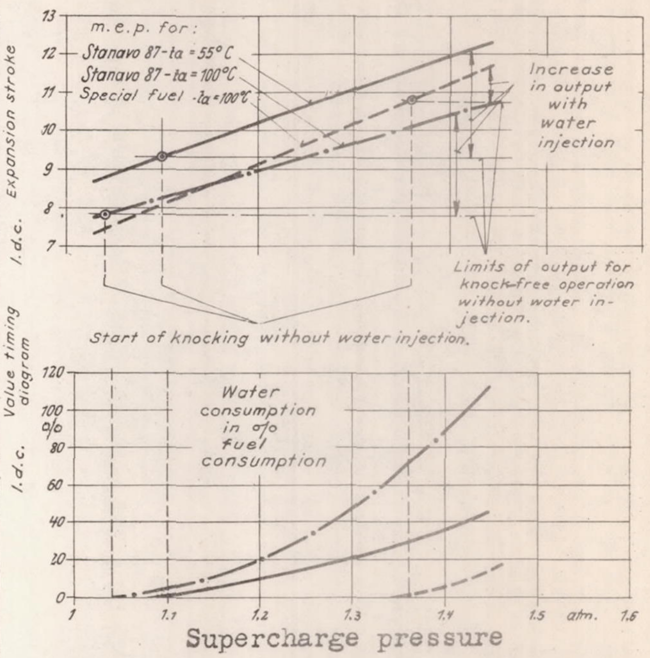
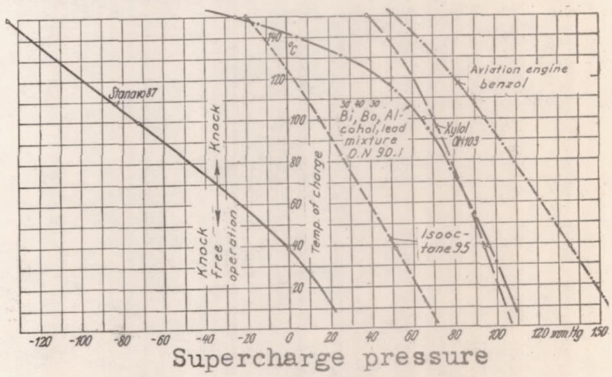


Figure 11.- Increase in output and water consumption for knock-free operation using water injection with an 87 octane aviation fuel and a three-component 90 octane mixture.



r.p.m.=1000; comp. ratio $\epsilon = 6.0$; full throttle setting; ignition 22° before u.d.c.; cooling temp. 100°C.

Figure 10.- Start of knocking for several fuels at various temperatures of the charge as a function of the pressure of the charge.

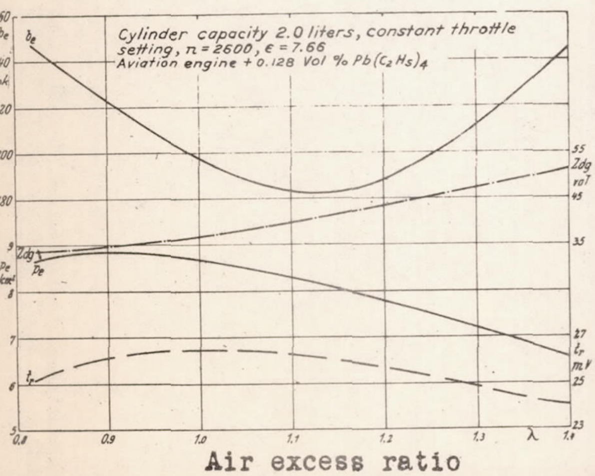


Figure 12.- Effect of air excess ratio on fuel consumption (single cylinder test).